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MEASUREMENT AND ANALYSIS OF CIRCUMSOLAR RADIATION

Donald Grether, David Evans, Arlon Hunt, and Michael Wahlig

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Donald Grether, David Evans, Arlon Hunt and Michael Wahlig

Lawrence Berkeley Laboratory
University of California
Berkeley CA 94720

BACKGROUND

Purpose

The purpose of this project is to provide measurements and analyses of the solar and circumsolar radiation for application to solar energy systems that employ lenses or mirrors to concentrate the incident sunlight. Circumsolar radiation results from the scattering of direct sunlight through small angles by atmospheric aerosols (e.g., dust, water droplets or ice crystals in thin clouds).

Concentrating solar energy systems will typically collect all of the direct solar radiation (that originating from the disk of the sun) plus some fraction of the circumsolar radiation. The exact fraction depends upon many factors, but primarily upon the angular size (field-of-view) of the receiver. A knowledge of the circumsolar radiation is then one factor in predicting or evaluating the performance of concentrating systems.

The project employs unique instrument systems (called Circumsolar Telescopes) that were designed and fabricated at LBL. The basic measurements are (1) the "circumsolar scan", the brightness of the sun and circumsolar region as a function of angular distance from the center of the sun and (2) the usual "normal incidence" measurement of a pyrheliometer. Both measurements are made for the entire solar spectrum, and (via colored filters) for eight essentially contiguous wavelength bands. Thus the measurements are applicable to systems in which the receiver is essentially wavelength-insensitive (e.g., central receiver) and to wavelength-sensitive systems (e.g., concentrating photovoltaics).

A secondary purpose of the project is to relate the data to the atmospheric processes that attenuate the solar radiation available to terrestrial solar energy systems.

Organization

The project was initiated in May, 1974; with the initial deployment of telescopes about two years later. The instruments have been operated since then at a variety of locations of relevance to concentrating solar energy systems. Arrangements are made for site personnel to provide routine maintenance of the instruments. LBL provides the technical and engineering effort and the spare parts inventory necessary to maintain the instruments in working order; monitors the data for quality control; and processes the data to the analysis stage. LBL undertakes a variety of analyses of the data for application to concentrating systems, and prepares the data in forms suitable for use at other DOE supported institutions.

Relationship to Other Projects

In conjunction with operating the telescopes, LBL has worked with the following DOE-supported projects: Solar 1, the Barstow 10 Mw_e Central Receiver pilot plant; the Advanced Components Test Facility at Georgia Tech; the Central Receiver Test Facility at Sandia, Albuquerque; the CPC project at Argonne National Laboratory; and the JPL Parabolic Dish Test Site at Edwards, California. Discussions are currently underway with McDonnell-Douglas regarding telescope operation (as of June 1, 1981) at Solar 1, and interfacing of the telescope to the facility's data acquisition system.

Institutions that have been provided data include: Sandia, Livermore (Central Recevier sensitivity analysis and quasi-minute-by-minute data for cloud transient studies); Sandia, Albuquerque (input to performance calculation program Helios); SERI (analysis of effect of circumsolar radiation on point-focusing systems); Watt Engineering (climatological-oriented study of circumsolar); JPL, Boeing, Georgia Tech, McDonnell-Douglas and Sanders Associates (analyses of concentrating systems).

Previous Results

Early results from the telescopes showed that there were clear-sky conditions for which the levels of circumsolar radiation were of negligible importance to concentrating systems. However, during less-clear sky conditions the circumsolar radiation could become tens of percent of the direct solar radiation. Under these conditions the circumsolar radiation would have to be taken into account in evaluating the performance of a solar plant.

Subsequent to these early results, the project has proceeded to establish in more detail the effect of the circumsolar radiation. Several approaches have been taken to establishing the average effect over time (e.g., months or years) on the performance of concentrating systems (1). In a generic approach, the system is described in terms of two simplified parameters, the operating threshold and the effective field-of-view of the receiver. Summaries have been presented, for example, of the fraction of the energy content of the solar plus circumsolar radiation that is "lost" (misses the receiver). The monthly average loss for a highly concentrating system (effective field-of-view of 0.75°) can range from a few percent to as much as 8%, depending on the telescope location and time of year. In a second approach (in conjunction with Sandia, Livermore) the loss for two specific central receiver designs for the Barstow pilot plant was determined. Monthly average losses ranged from 1% to as much as 6%, depending upon the location, season, and design.

Analyses have been made of the systematics of the circumsolar radiation. The objective is to develop quantitative relationships between the circumsolar radiation and atmospheric and solar parameters; relationships that can be used to estimate the circumsolar level when actual measurements are not available. One approach has been to examine empirical correlations of the circumsolar radiation with other parameters such as the pyrheliometer reading, air mass, season, etc. One result, for example, is that a plot of the circumsolar level vs. pyrheliometer reading shows distinct patterns, with the different parts of the plot corresponding to different types of atmospheric conditions. In another approach, calculations have been performed to relate the data to the atmospheric scattering processes. For example, the angular distribution of the circumsolar radiation has been compared to the predictions of the Mie theory of light scattering from small particles.

DESCRIPTION

Instrumentation, Measurements, and Data Logging

Each instrument system consists of a scanning telescope mounted on a precision solar tracker, an electronic controller, and various pieces of auxiliary equipment. The latter include a pyrheliometer to provide the usual "normal incidence" measurement as well as the calibration for the telescope scan, and two pyranometers (one tracking the sun and one mounted in the usual horizontal position). The telescope scans thru a total angle of six degrees, with the sun at the center of the scan. A digitization of the brightness of the solar or circumsolar region is taken every 1.5 minutes of arc. One scan takes about one minute of time. The telescope and pyrheliometer have matched ten position filter wheels: one clear (or open) filter, eight colored filters, and one opaque filter used to monitor detector noise. The data are recorded on magnetic tape using a Kennedy incremental-digital tape drive.

A sunphotometer, on loan from NOAA, was recently mounted on one of the telescopes (Scope 3). To allow for automated operation, the photometer was placed in an environmentally sealed and temperature controlled housing, and the output connected to the data acquisition system.

Support facilities at LBL include the Solar Energy Program's electronics laboratory; the mechanical, electronic, and optical shops of the Special Projects group (which fabricated the instruments and provides maintenance and development support); a roof-top area for instrument calibration and testing; and the Laboratory's computer facilities for data processing and analysis.

Measurement Sites

The budget for FY80 was not sufficient for LBL to support all four telescopes. Sandia, Albuquerque agreed to operate one, but only in conjunction with tests at the Central Receiver Test Facility (thus concluding the long-term data base for this location). LBL continues to support the instrument at Atlanta, and a recently-upgraded instrument that was installed at the beginning of the fiscal year at the JPL Parabolic dish test facility at Edwards. The instrument at Barstow was returned to

LBL. The following table summarizes the telescope locations to date.

Scope	Site	Motivation	Dates
1	Boardman, OR	Boeing heliostat test	2/77 - 5/77
	Colstrip, MT	NOAA Atmospheric tests	5/77
	Atlanta	ACTF (a), humid climate	6/77-present
2	Albuquerque	CRTF (b), high-desert climate	5/76 - 10/79
	Albuquerque	CRTF tests	11/79-present
3	Ft. Hood, TX	TES (c), warm cloudy climate	7/76 - 8/77
	Argonne, IL	Cool cloudy climate	8/77 - 10/78
	Berkeley, CA	Rehabilitate & upgrade	11/78 - 10/79
	Edwards, CA	JPL PDTF (d), Mojave climate	11/79-present
4	China Lake, CA	Mojave desert climate	7/76 - 5/77
	Barstow, CA	Mojave, 10 Mw_e pilot plant	5/77 - 10/79
	Berkeley, CA	Storage	11/79-present

(a) Advanced Component Test Facility at Georgia Tech
(b) Central Receiver Test Facility at Sandia Laboratories
(c) Total Energy System (proposed)
(d) Jet Propulsion Laboratory Parabolic Dish Test Facility

Quality Control, Data Processing, and Data Availability

Data tapes are shipped to LBL from the various sites at the end of each week. At LBL, the data undergo an initial computer processing to determine if the telescope is experiencing any difficulties. If so, corrective actions are first attempted by contacting site personnel. Should the problem prove intractable by this approach, then an LBL staff member travels to the site and undertakes the necessary repairs.

At the time of the initial processing, the data are transferred as-is from the original, low density magnetic tapes to high density ones called RAW tapes. Later, the information from the RAW tapes, with various organizational problems (e.g., incorrect dates) fixed, is rewritten onto so-called FIX tapes. At this point calibration factors are applied, and the data are condensed and written onto a preliminary version of the Reduced Data Base (RDB). Various statistical methods are then employed to look for and, when necessary, devise correction factors for faulty data. A revised RDB is then produced, and the data are ready for analysis.

The RDB, which contains one record for each ten minute measurement cycle of the telescope, is available. However, for many applications hourly average data are sufficient or preferable. Thus a Hourly Data Base is also available, variations of which have been the means of providing data to SERI, Watt Engineering, and Sandia, Albuquerque. For specific time periods (e.g., tests of concentrating systems) data are available in the form of graphs and computer printout of individual scans of the telescope, as well as magnetic tape.

Research Tasks, Data Applications and Models

An on-going task is the summarizing of the data along the lines described above (BACKGROUND). These approaches have established a baseline for identifying any changing conditions at long-term sites, and for comparing different climate regions. In addition, the approaches themselves continue to be developed.

A second area is the analysis of the systematics of the circumsolar radiation (also above). One aspect involves developing a model that could be used to estimate the circumsolar radiation given other, more readily measured, parameters. Work in this area has been at a low level this fiscal year.

A major effort this fiscal year has been the analysis of the spectral (filtered) data, for application to wave-length sensitive systems. Extensive use is made of a model of the solar spectrum (referred to as SSM for Solar Spectral Model) that combines the atmospheric transmission computer code LOWTRAN (2) with an extraterrestrial solar spectrum (3).

SUMMARY OF RESULTS (FY 1980)

Data Collected/Processed

Data were obtained from the two telescopes (Atlanta and Edwards) supported this fiscal year by LBL. The data were processed to the preliminary RDB stage up thru June, 1980 and to the revised stage up thru December, 1979.

Presentation and Discussion of Results

Summaries of the type discussed under BACKGROUND were prepared for the data up thru December, 1979. Sample results are shown in Fig. 1 for the Mojave desert area (the small, vertical arrows indicate the changes from one location to the next). Displayed in Fig. 1(a) is the monthly average circumsolar ratio; defined as the monthly total circumsolar (from the edge of the sun out to 3^{o}) radiation, divided by the direct solar (coming from the disk of the sun) plus circumsolar radiation. This quantity is approximately the same as the overestimate that a pyrheliometer would make in estimating the monthly total direct solar (from the disk of the sun) radiation. Fig. 1(b) shows the ratio of the monthly total direct solar radiation to the extraterrestrial value. This quantity (which is similiar to the commonly-used K_t of Ref. 4) compensates for the seasonal changes in the length of the day and the varying earth-sun distance, and hence can be taken as an indicator of "cloudiness." The circumsolar ratio shows a distinct seasonal dependence, with a winter peak of as much as 7% and summer minima of about 2%. There is also a noticable correlation with the total/extraterrestrial parameter; with a tendency for cloudy months to have high circumsolar levels. Comparable data for Albuquerque (not shown) do not have any obvious seasonal dependence. Rather, the circumsolar ratio shows a trend of increasing values from 2-3% in May-June, 1976 to 4-5% in February-March, 1977, and then, with considerable fluctuations, a more or less steady value thereafter.

A considerable effort this fiscal year was devoted to analyzing the colored filter pyrheliometer data. The work will be briefly discussed here based on the data from Scope 4 (China Lake and Barstow). The first step was to characterize the transmission function (transmission vs wavelength) of each filter during the period of operation of the telescope (July, 1976 thru October, 1979). Spectrophotometer measurements of the transmission of the filters were made at LBL this fiscal year. Comparisons to measurements provided by the manufacturer when the filters were new suggested that many of the filters had experienced a change in overall transmission. A method was then developed to use the pyrheliometer data to track the change. Using a modified "Langely Plot" approach, the ratios of colored-filter to clear-filter pyrheliometer values for each month of clear-sky data were extrapolated to zero air mass (no atmosphere). The extrapolated value, C, is expected to be relatively independent of actual atmospheric conditions but quite sensitive to changes in filter characteristics. Figure 2 shows C (the small squares) plotted from July, 1976 thru October, 1979 for two of the filters. The filter for Fig. 2(a) is observed to have experienced an abrupt reduction in transmission in November, 1976. Fig. 2(b) shows more typical behavior; a steady decrease in transmission over time. To account for such effects ad-hoc "aging" factors were adapted, with a linear dependence generally adequate to describe the data. The LBL spectrophotometer measurements, together with the aging factors, are then taken as specifying the filter transmission functions. As a consistency check, the SSM (Solar Spectral Model, see above) was used to generate nominal clear-sky solar spectra, which were convolved with the transmission functions to produce modeled pyrheliometer readings. These were then extrapolated to zero air mass in the same manner as for the actual data. The modeled values, shown as solid curves in Figure 2, are in quite good agreement with the data. [The apparent seasonal variations, which appear in both the real and modeled data, are artifacts of the extrapolation process.]

Given a knowledge of the filter transmission functions, the second step was to invert the pyrheliometer readings to obtain the (spectral) distribution of energy in the solar spectrum. Since the transmission functions are non-ideal in shape (as is the case for all physically realizable filters) the inversion cannot be carried out exactly and an estimation method must be used. The method developed here, described in detail in Ref. 5, involved calculating an effective transmission over a nominal pass band for each filter. The calculation uses an SSM solar spectrum so as to take into account in an approximate way the shape (but not the magnitude) of the actual solar spectrum in the region of the filter. The results have been shown to be insensitive to the details of the model. The energy content of the solar spectrum within the nominal pass band is obtained by (i.e., the inversion is carried out by) dividing the pyrheliometer reading by the effective transmission.

Fig. 3 displays in bar graph form inverted values for two sequences of colored-filter clear-sky pyrhelimeter readings. Superposed on the data is an SSM modeled solar spectrum for nominal clear-sky conditions. For ease of comparison, the average of the modeled spectrum over each pass band has been plotted as a square at the center of the band. The two data sequences and the modeled spectrum are for the same air mass value and have nearly the same clear-filter pyrheliometer readings (about 940 w/m^2). Of note is the variation in spectral composition of the data, with one sequence in quite good agreement with the model, and the other having a relative depletion in the wavelength region around 1.0 microns.

Recommendations and Future Plans

For FY 1981 plans are to continue the operation of the instruments at Atlanta and in the Mojave area, with the telescope at Edwards to be moved to the Barstow Pilot Plant by June, 1981. In addition, the telescope currently at LBL would be rehabilitated & upgraded and located at SERI. Work would continue on the analysis of the clear-filter data, with an increased emphasis on modeling the systematic behavior of circumsolar radiation. The effort on the colored-filter pyrheliometer data will be concluded on the data available to date, with summaries produced of the energy content of the solar spectrum for various locations, atmospheric conditions, etc. Some attention will be given to the colored-filter scan data.

It is proposed that a new instrument be designed as part of the FY 1981 program. The design would incorporate our knowledge of the character of circumsolar radiation as obtained with the current instruments, and a control system based on modern micro-processor devices. The instrument would be simplier to operate and maintain, and would take fewer data points but over a somewhat increased range of parameters. Actual construction would be deferred until FY 1982.

ACKNOWLEDGEMENTS

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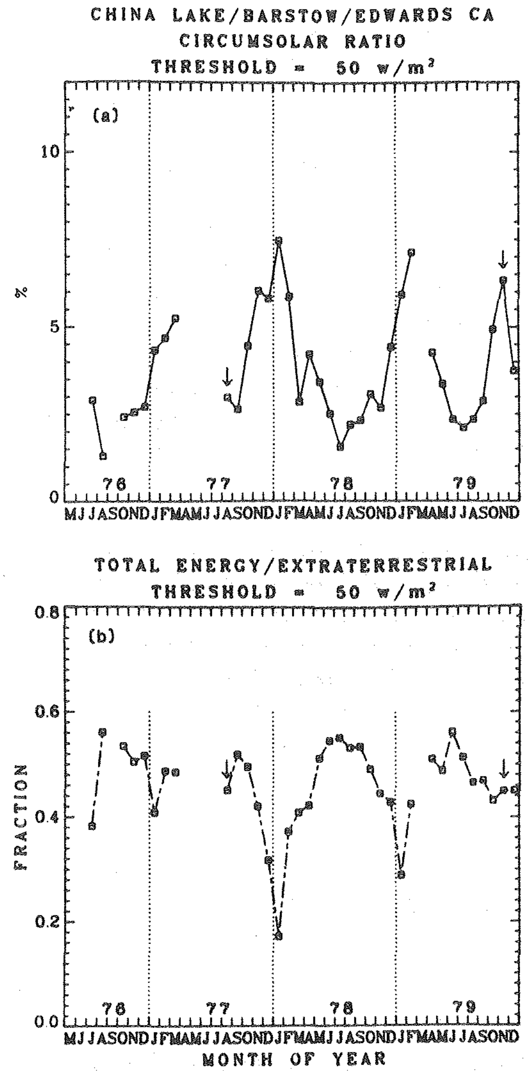

Figure 1

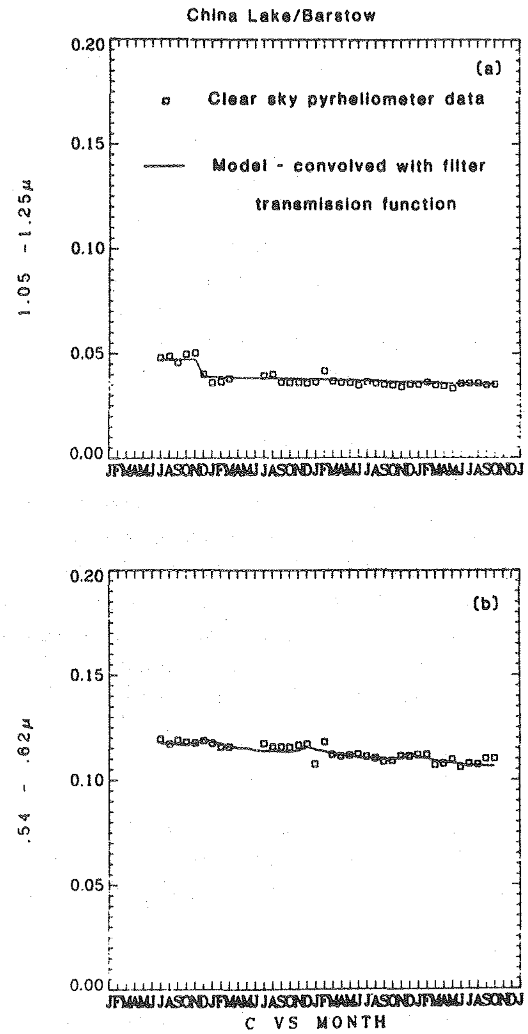

Figure 2

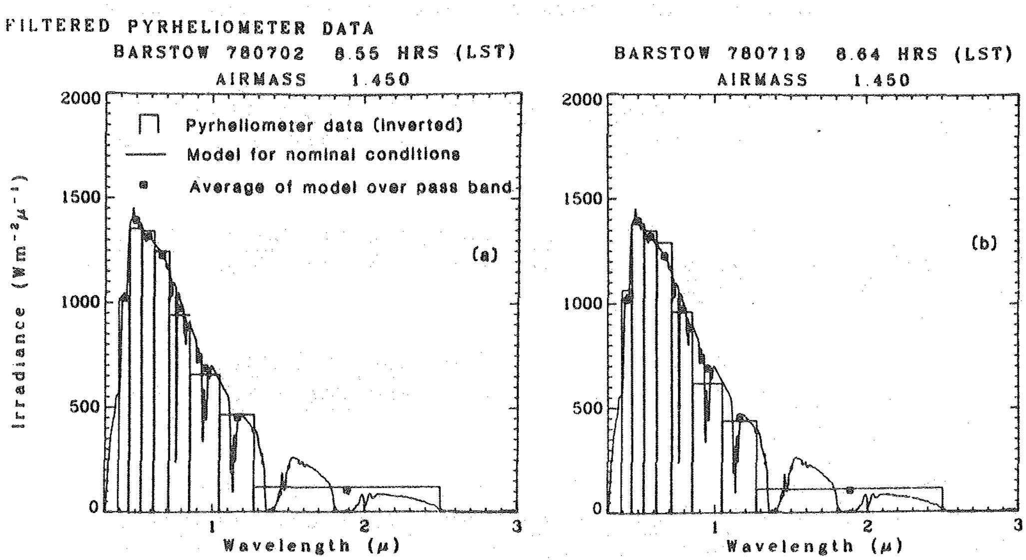

Figure 3